CHAPTER XVII.

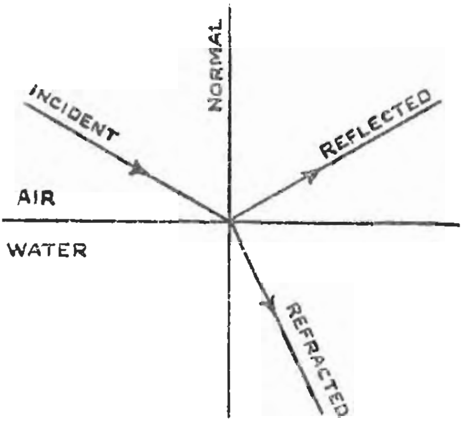
ELECTROMAGNETIC WAVES.

717. The conception of wave motion as a means of transferring energy from one point to another was explained in Chapter I, and it was pointed out that wireless radiation was of the same nature as heat and light radiation, the only difference being in the frequency of the waves. The energy transmitted by such wave motion is known as electromagnetic energy, since its production is associated with the presence of electric and magnetic fields. These fields may be due to the electrical structure of the atom or molecule, as in the case of light and heat rays, or of the large scale type produced in electrical oscillatory circuits when wireless waves are radiated. Waves which transmit electromagnetic energy are called electromagnetic waves. Other types of wave motion capable of transmitting energy, such as sound and water waves, are dependent on a material medium for their propagation, but electromagnetic waves can be propagated in a vacuum. The difficulty of conceiving a wave motion without a medium in which it is passed on from point to point has led to the postulation of a non-material medium called the æther, which must be assumed to permeate all space. It should be emphasised that properties similar to those of material substances cannot be attributed to the æther, and the attempt to do so produces absurd results. The conception of the æther is merely another way of saying that space empty of all material substances still possesses the property of allowing electromagnetic waves to travel through it.

When it is considered as the vehicle of transmission of electromagnetic vibrations, empty space is generally known as the free æther. All electromagnetic waves, no matter what may be their frequency, travel at the same speed in the free æther. This velocity, as determined experimentally, is very nearly 3×10^8 metres per second, this figure being generally employed in wireless calculations. The more accurate figure is $2 \cdot 9982 \times 10^8$ metres per second.

When electromagnetic waves are travelling through a material medium, *e.g.*, a brick wall, it must still be considered that the actual medium in which they are propagated is the æther. It is, however, no longer free æther, but is modified by the presence of the material occupying the same space. As a result, the transmission of the electromagnetic waves is also modified by the material. The effects produced are most easily realised by considering the case of light waves, since they are then visible.

718. Reflection.—It is hardly necessary to explain the meaning of reflection. When a billiard ball strikes a cushion its direction of motion is reversed. In the same way an electromagnetic wave trying to pass from one material medium to another may be turned back at the common surface of the two media. In the case of a light wave arriving obliquely at a point on the surface of a mirror, the reflected wave comes off at the same angle on the other side of the line through the point perpendicular to the mirror as the arriving



Reflection and Refraction.

Fig. 427.

or "incident" ray, as shown in Fig. 427. Because of this the reflected image of an object appears to be at the same distance behind the reflecting surface as the object is in front of it. Generally the wave is only partly reflected at the surface, and a part of its energy passes on into the second medium.

719. Refraction.—If a walking-stick is partly immersed in water, it no longer appears to be straight. The part under water appears to run in a different direction from that in the air. The light waves, by which the stick is made visible, alter their direction of propagation when they pass from air to water and *vice versa*, and so the stick appears to be bent. The reason for this is that the waves do not travel with the same velocity in the two media. In this case they travel more slowly in water than in air, (or rather, more slowly in æther as modified by water than in æther as modified by air), and the effect is that the direction of propagation in water is bent in towards the normal, or line drawn at right angles to the air-water surface through the point where the stick enters the water. The waves are said to be refracted, and the ratio of the velocity of the waves in free æther to the velocity of the waves in a material medium is known as the refractive index of the medium. Since the waves travel more slowly in water than in air, the refractive index of water is greater than that of air. The actual figures are 1·33 for water and 1·00029 for air (at normal pressure and temperature).

$$\text{Thus } n \text{ (refractive index)} = \frac{3 \times 10^8 \text{ metres per sec.}}{\text{velocity in medium}},$$

$$\text{or velocity in medium} = \frac{3 \times 10^8 \text{ metres per sec.}}{n}.$$

From the nature of electromagnetic waves we should expect that their velocities in various media would depend on the electrical and magnetic properties of the media, and it can be shown that if K is the dielectric constant of a medium and μ is its permeability, the velocity of electromagnetic waves in the medium is $\frac{3 \times 10^8}{\sqrt{\mu K}}$ metres per second. Since μ and K are both taken as unity for a vacuum, this gives the velocity of electromagnetic waves in free æther as 3×10^8 metres per second, as previously stated.

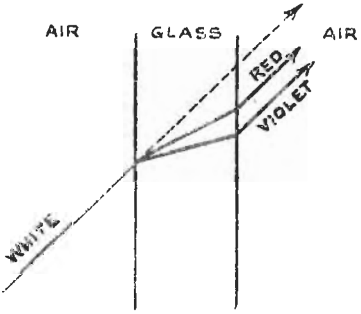
The permeability, μ, is approximately unity except in the case of ferromagnetic metals, and so the velocity in a given medium may be taken to be $\frac{3 \times 10^8}{\sqrt{K}}$ metres per second.

It follows from this that the refractive index of a medium is equal to the square root of its dielectric constant,

$$i.e., \; n = \sqrt{K}.$$

This formula is only strictly correct for a perfect insulator. For poor insulators and conductors it must be modified to take account of their conductivity.

720. Dispersion.—The dielectric " constant " of an insulator is not constant, but varies with the frequency of the alternating P.D. applied across it. Thus a material medium has a different K for electromagnetic waves of different frequencies, and therefore a different refractive index. The dielectric constant of distilled water, for example, as deduced from steady potential measurements, is about 80. For alternating potentials of the frequency of light waves it is in the neighbourhood of 2, ($n^2 = 1 \cdot 7$). In other words, the velocity of an electromagnetic wave in any medium except the free æther depends on its frequency. This can be readily seen in the case of light waves by examining the light from the sun through a glass plate. Sunlight consists of a very large number of light vibrations of different frequencies. These all travel with the same velocity through free space, and with sensibly the same velocity through air, owing to its small refractive index, and so combine to give the impression of white light. The differences in velocity of the component vibrations of different frequencies are, however, appreciable in the case of glass. In consequence, these vibrations are refracted through different angles in passing through the glass, and re-appear at different points on the other side of the plate, as shown in Fig. 428. Differences in frequency in the visible range appear to the eye as differences in colour, and so a series of differently-coloured images of the sun will be seen side by side. The white light is said to be resolved into a spectrum. In practice these images will largely overlap each other. To produce a good spectrum, a ray of sunlight entering a dark room through a very narrow slit should be allowed to fall on a glass prism. A series of images of the slit will then be seen, appearing as parallel differently coloured bands of light. The red band is least, and the violet band most, deviated from the direction of the original white light.



Dispersion.

FIG. 428.

721. Total Reflection.—It has been seen that a light wave in passing from air to water is refracted towards the normal (Fig. 427). Conversely, a wave from water to air is refracted away from the normal. As the direction of the wave in water becomes more oblique to the normal, the angle made with the normal by the refracted ray in air becomes correspondingly greater, and eventually a point is reached when the wave, on emerging into air, just grazes the common surface, *i.e.*, is at right angles to the normal. If the obliquity of the wave in water is increased further, no wave can then emerge into the air, *i.e.*, the wave is totally reflected at the common surface. The angle made by the incident ray with the normal when this occurs is known as the critical angle.

This phenomenon can only occur when the refracted wave makes a greater angle with the normal than the incident wave, *i.e.*, when the refractive index of the first medium is greater than that of the second medium. In other words, total reflection can only occur when the electromagnetic waves attempt to pass into a medium in which they would travel more quickly.

722. These various effects influence the propagation of wireless waves just as they do the propagation of light waves, although the amount of importance attaching to them is different owing to the very different frequencies of these two kinds of electromagnetic vibration. As a simple example in the case of wireless waves, we may consider the effect of endeavouring to propagate them in a perfect conductor. The dielectric constant K of a perfect conductor is infinite, for no potential difference can be established across it, and so the velocity of electromagnetic waves in it, namely $\frac{3 \times 10^8}{\sqrt{K}}$ metres per second, is zero. In other words, these waves cannot pass through a perfect conductor. It is well known that good conductors, such as copper, will not allow wireless waves to pass through them, and so are extensively used for screening purposes. In such cases the energy in the waves is partly reflected and partly absorbed in the screen. The alternating field produced by the wave in the metal sets its free electrons into oscillation, and the damping out of these oscillations by collisions with molecules converts the energy into energy of molecular vibration, *i.e.*, heat energy.

To illustrate the effect of the different frequencies of electromagnetic waves on their propagation in material media, it may be mentioned that a brick wall is completely opaque to light waves, but allows wireless waves to pass through it, as evidenced by the possibility of reception using indoor aerials, such as are common in portable receivers.

723. An attempt will be made in the next few paragraphs to give some picture of how an oscillatory current flowing in an aerial circuit gives rise to electromagnetic radiation. It must be pointed out, however, that any such picture is crude, and in some ways even misleading. The real proof of the theory depends on mathematical analysis beyond the scope of this book. It was first developed by Clerk Maxwell in 1864 from the general laws of electricity and magnetism, and so the set of relations which he derived, and which are the basis of electromagnetic wave theory, are known as Maxwell's Equations. From these equations it can be shown that changing electric fields and the changing magnetic fields they produce must give rise to electromagnetic radiation, whose velocity of propagation can be determined from the electrical constants of the medium. This calculated velocity was found to be the same as the measured velocity of light waves, and so gave rise to the theory that light waves were of electromagnetic origin, and to experimental attempts to produce similar radiation by means of electrical circuits. The successful production of such radiation by Hertz laid the foundations of wireless telegraphy.

724. Radiation.—Let us take as the simple type of oscillatory circuit with which to illustrate electromagnetic radiation, a condenser whose plates are connected by a vertical wire which has a certain amount of self-inductance (effectively an aerial circuit). An alternator is included in the circuit to represent a source of alternating E.M.F. of high frequency, the frequency being that to which the circuit is resonant. This system is then effectively that of a C.W. oscillator maintaining an oscillation in an aerial circuit.

We shall examine the distribution of the electric field round such an aerial, and its changes during one cycle of the applied E.M.F.

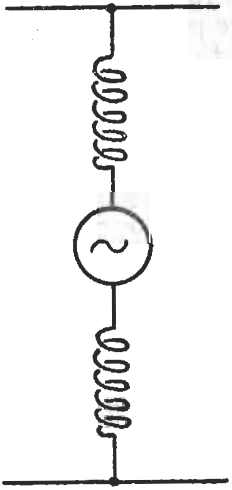


FIG. 429.

At the start of the cycle let the condenser be charged to its maximum P.D., so that the top plate is positive to the bottom plate, and the current is zero. At this instant we may regard the field in the vicinity of the aerial as being entirely electric, and lines of electric strain to be connecting each positive ion on the upper plate to its "opposite number," a negative ion on the lower plate, as in Fig. 430 (*a*).

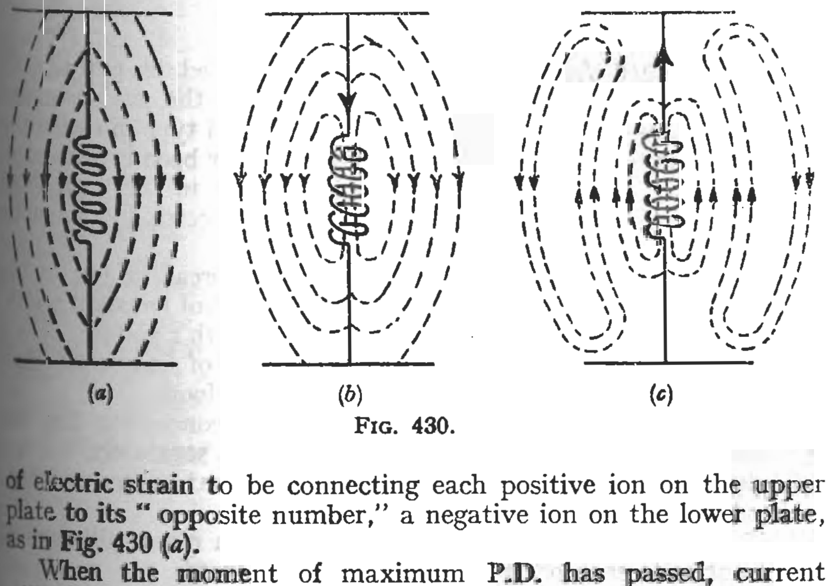


FIG. 430.

When the moment of maximum P.D. has passed, current will start to flow downwards. The electric field starts to collapse, and this effect may be represented as in Fig. 430 (*b*), showing the ends of the lines of force coming together along the wire. The current continues to flow after the potential difference across the condenser is reduced to zero, and in so doing starts to charge up the condenser to the opposite polarity, giving rise to new lines of force in the opposite direction to the previous field. We may regard the collapse of the initial field as lagging a little on the changes in potential which cause it to take place, and with this assumption the new electric field starts to build up before the first one has disappeared. The first disturbance is then forced outwards in the form of closed loops by the new electric field, for the direction of the lines in the inner surface of the first and the outer surface of the second are the same.

As the current oscillates in the circuit, a series of closed loops of electric stress is sent off into space radially from the oscillating system, each set repelling its predecessors to make room for the latest-born, and representing lines of force in the opposite direction to the sets next in front and in rear.

Similarly we must regard the circuit as being surrounded by rings of changing magnetic stress, whose intensity varies with the current strength, and whose direction alternates in the same way as the direction of the electric field alternates.

Further, these magnetic lines of force are horizontal, being in a plane at right angles to the current-carrying wire, and consequently at right angles to the electric lines of force. This type of oscillation is produced by an oscillating system excited in the middle, and a practical application may be found in the case of a trailing aeroplane aerial.

725. Earthed Aerial.—The aerial system used in practice, in which the earth is utilised as the bottom plate of the condenser, can be regarded as the upper half of the symmetrical type of oscillating system excited at the middle which has so far been investigated. This assumes that the capacity is concentrated in the "roof" of the aerial. The consequent distribution of the electric and magnetic fields is somewhat as shown in Fig. 431.

The full lines represent the electric field spreading out in the form of annular loops of ever-increasing height but constant width. It may be taken as vertical at points near the earth's surface These loops are accompanied by horizontal loops of magnetic flux, spreading out from the aerial with the electric loops.

It is important to grasp the fundamental conception that the **moving electric and magnetic fields do not exist separately,** but are simply different ways of expressing the fact that energy is transmitted by an electromagnetic wave.

They are therefore **in time phase with each other, although at right angles to each other in space.** In other words, the maximum strength of magnetic field occurs when the electric field is also a maximum.

In the surface of the earth there will be circular bands of current flowing alternately radially outwards and inwards.

The velocity with which the whole system moves outward is (approximately) 3×10^8 metres per second. The frequency with which consecutive bands of maximum electric or magnetic field are generated is the frequency of the current in the oscillatory system, and the radial distance between two consecutive maxima of electric or magnetic field in the same direction is the wavelength of the electromagnetic wave. The strength of the electric or magnetic field varies sinusoidally with respect to time at any given point remote from the transmitter, and sinusoidally with respect to distance measured outwards from the transmitter at any given time, (neglecting the attenuation in amplitude discussed in later paragraphs).

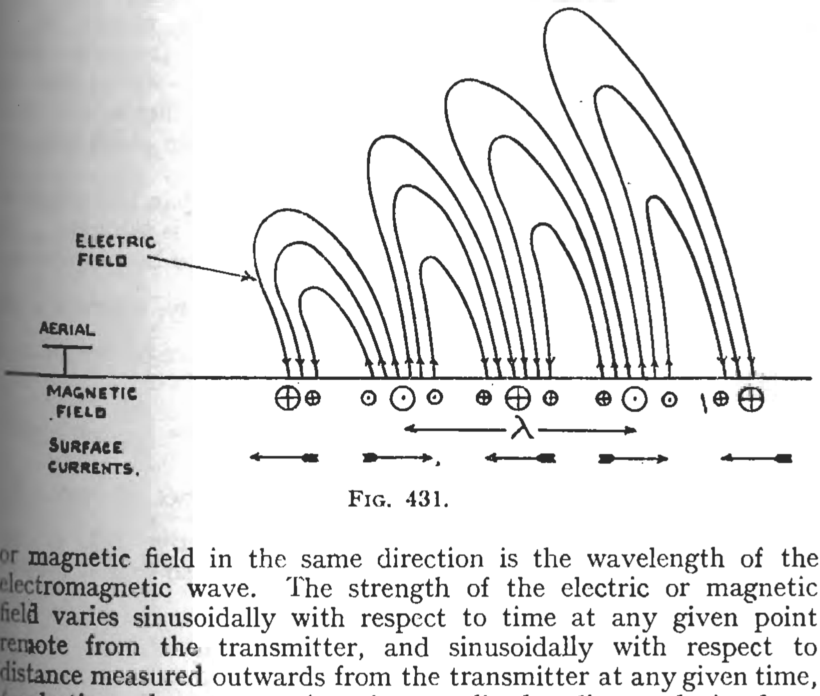


Fig. 431.

726. Radiation and Induction.—It is important to distinguish between " radiation " and " induction."

The principles of induction have already been explained in earlier chapters.

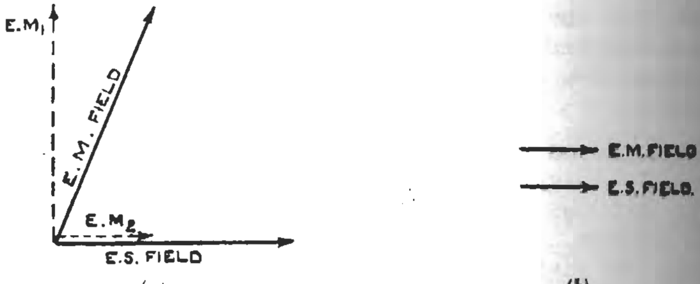
It may be advisable to state once again the essential characteristics associated with radiation, so as to draw the necessary comparisons with induction.

Radiation is a moving disturbance of the æther, in which varying states of electric and magnetic stress are propagated outwards from the oscillating system, and represent an actual dissipation of energy. The two fields, which are simply two different ways in which the phenomenon may be regarded, are **in time phase** with each other but **in space quadrature** (at right angles), and both are at right angles to the direction of propagation. It can be shown that the intensity of the fields associated with radiation over a perfectly conducting surface falls off **inversely as the first power of the distance** from the oscillating system producing them.

Induction represents a variation of electric and magnetic fields in which there is no dissipation of energy. The electric and magnetic fields are **in both time and space quadrature** (90° out of phase in time, and at right angles to each other in space), and energy simply oscillates from one to the other without any being lost. We have already met this effect in the theory of the oscillations set up in an LC circuit in which resistance losses are assumed to be zero (Chapter VII). It can be shown that the intensity of the electric or magnetic fields of induction at any point varies inversely as the square of the distance of the point from the oscillating system.

Near the aerial the inductive field is stronger than the radiative, and at a great distance from the aerial the reverse is the case. The actual strengths of the two fields can be proved to be proportional to $\frac{2\pi hI}{\lambda d}$ (radiative) and $\frac{hI}{d^2}$ (inductive) respectively, where h is the height of the aerial, I the current, and d the distance of the point at which their intensities are measured.

It follows that at a distance where $\frac{2\pi hI}{\lambda d} = \frac{hI}{d^2}$, *i.e.*, where $d = \frac{\lambda}{2\pi}$, the intensities are equal, while at a distance of even a few wavelengths, say 5λ, the intensity of the inductive field is only about one-thirtieth of that of the radiative field, so that it may be neglected in comparison with the latter.



(*a*) (*b*)

FIG. 432.

At any point, the complete field is, of course, the resultant of the inductive and radiative components. Taking the electric field as a basis of reference, the magnetic field is the resultant of two components, one in phase and the other 90° out of phase (as regards time) with it.

Very near the aerial the inductive component is the larger, so that the resultant magnetic field is as illustrated in Fig. 432 (*a*);

far from the aerial the inductive component may be neglected altogether, so that the magnetic and electric fields are effectively in time phase.

The intensity of the radiative field will be further referred to quantitatively in the chapter on aerials.

727. An electromagnetic wave of the type shown in Fig. 431 may be represented diagrammatically as in Fig. 433. The vertically oscillating electric field is shown by the vertical vector OZ, and the horizontally oscillating magnetic field by the horizontal vector OX, which is really perpendicular to the plane of the paper. The direction of propagation of the wave, OY, is at right angles to the plane of OX and OZ. The amplitude of the electric field $\mathcal{X}$, measured in electrostatic units, is equal numerically to the amplitude of the magnetic field $\mathcal{H}$, measured in electromagnetic units. When both $\mathcal{X}$ and $\mathcal{H}$ are expressed in the same units, the numerical relation connecting them is $\mathcal{X} = \mathcal{H} \times 3 \times 10^{10}$.

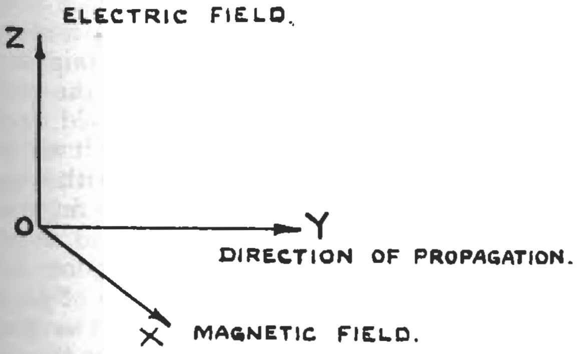


FIG. 433.

It may help to fix ideas of the nature of the wave and its propagation if a numerical example is taken. Consider a wave of frequency 250 kc/s., and therefore of wavelength 1,200 metres in the free æther, and approximately of this wavelength when travelling through the atmosphere close to the surface of the earth. The electric and magnetic fields are in time phase, and at some instant they will have their maximum values simultaneously at the point O in Fig. 433. Suppose that times are reckoned from this instant. The time of a complete cycle of values of the wave fields for a 250 kc/s. wave is $\frac{1}{250{,}000}$ second, or 4 microseconds. After a quarter of this time, *i.e.*, one microsecond, the two fields at O will have decreased to zero. They then reverse in direction, and start to increase in magnitude, and after another millionth of a second they attain maximum values in the reverse direction. In this time, 2 microseconds, the wave has travelled 3×10^8 metres per second $\times 2 \times 10^{-6}$

seconds = 600 metres, or half a wavelength, and so the fields at a point P, 600 metres from O in the direction of propagation, have their maximum values 2 microseconds after similar maxima occur at O. As this time corresponds to maximum reversed values at O, it follows that the fields at P and O at the same instant are 180° out of phase.

In 4 microseconds the fields complete a cycle, and their values at O are the same as their initial values. The wave has travelled 1,200 metres in this time to a point Q, say. The fields at O and Q, 1,200 metres apart, are therefore in time phase.

Thus the time lag of the fields at a point R on those at O depends on the time taken by the wave to travel from O to R. 1,200 metres from O, the fields are in phase with those at O; 600 metres from O, they are 180° out of phase; 300 metres from O, they are 90° out of phase; and in the general case the time lag of the fields at R on those at O is $\frac{360d}{\lambda}$ degrees, or $\frac{2\pi d}{\lambda}$ radians, where λ is the wavelength and d is the distance between O and R.

We may also consider the reflection of such a wave when it arrives at the surface of another medium, in the simplest case when the direction of propagation is perpendicular to the surface. The direction of propagation is then completely reversed, and the wave travels back along its original path. From Fig. 433 it will be seen that the electric and magnetic vectors are arranged with respect to the direction of propagation like the forefinger, middle finger and thumb of the right hand extended as in Fleming's rule, and, as in that case, reversing any two of the three quantities together does not alter the direction of the third. Thus, when the direction of propagation is reversed, the direction of either the electric field or the magnetic field will be reversed, but not both. Actually it is the electric field which reverses in direction, or, in other words, changes its phase by 180° at a reflecting surface; the magnetic field is unaltered in direction.

728. Polarisation.—A wave of the type considered above, in which the electric field vector is vertical, is called a vertically polarised wave. When the electric field is horizontal, the wave is said to be horizontally polarised. In these cases the vibration of the æther "particle" undergoing the wave motion may be considered to be either up and down or backwards and forwards horizontally, and so it is a linear vibration. In certain circumstances, however, more complicated motion of the æther is produced. For instance, the æther "particle" may move in a circle or ellipse. The wave is then said to be circularly or elliptically polarised. These various types of polarisation may be illustrated by fixing a long rope at one end. If the free end is then waved up and down, the wave motion in the rope is vertically polarised; if backwards and forwards horizontally, a horizontally polarised wave is produced, Circular polarisation may be imitated by moving the free end of the rope in a vertical circle.

The wave radiated from a vertical aerial over the surface of a good conductor, such as sea water, may be taken as a good approximation to a vertically polarised wave.

729. Attenuation. Effect of the Earth.—It has been seen that the bases of the electromagnetic waves move outwards from the aerial over the surface of the earth, and also that high-frequency currents are set up in the earth.

On the assumption that the surface of the earth is a perfect conductor, no energy is lost as a result of these currents. This assumption is not justified in practice, because the conductivity of the earth varies widely, depending on its nature. Thus the sea is a very good conductor, and we may pass through the various stages of fresh water, damp soil, etc., to very dry soil, which is a very bad conductor. In some places the surface materials of the earth are, in fact, good insulators.

The attenuation of the electromagnetic wave therefore varies according to the type of surface over which it is passing. As the energy which is being dissipated is supplied by the electromagnetic wave itself, it follows that the wave front must become tilted forward in order to give a horizontal component of the electric field, and so does not remain perpendicular to the earth's surface. It can be shown that the higher the conductivity, the less is the depth to which energy can penetrate, and the less are the losses. For example, a theoretical calculation shows that a station having a range of 1,000 miles over a perfectly conducting expanse would have a range of :—

920 miles over sea water ;
700 miles over fresh water or very wet soil ;
560 miles over wet soil ;
270 miles over damp soil ;
150 miles over dry soil ;
55 miles over very dry soil ;

and these figures accord very well with practical experience.

It can further be shown that the higher the frequency of the waves, the greater are the losses, and so the range of a wave travelling over the earth's surface decreases as the frequency increases.

Since the wave front may be regarded as being tilted forward, so that the bottom of the wave is somewhat retarded, it is obvious that signals may be received by insulated wires buried in the ground or under water. The depth to which effective penetration is possible decreases with conductivity, as was stated above, and the maximum depth possible in salt water may be taken to be about five metres.

The tilting of the wave front also helps to make the waves follow the curvature of the earth.

As a general conclusion, one expects to get the longest ranges over sea, and range falls off if dry ground intervenes.

Great difficulty occurs in communication between two stations which have jungle or dense undergrowth intervening, especially if the jungle grows close up to the station.

A tremendous absorption of energy occurs; moreover, there seems to be a layer of air, level with the tree tops, at the same potential as the earth, and the wave travels along the surface of this, and does not influence a receiving aerial unless the latter be a good deal higher than the trees.

730. Screening.—It is a well-known fact that if a ship is lying close to a very high piece of land, or in a land-locked harbour surrounded by high cliffs, her reception of signals is greatly diminished, while if she steams away clear of the land by a few miles she picks up signals once more. This occurs for two reasons :—

(*a*) The electric field of the æther wave is deflected by the land, as illustrated in Fig. 434. This means that the electric lines of force acting on the aerial of the ship (A) are in a horizontal instead of a vertical direction, and thus are made very ineffective.

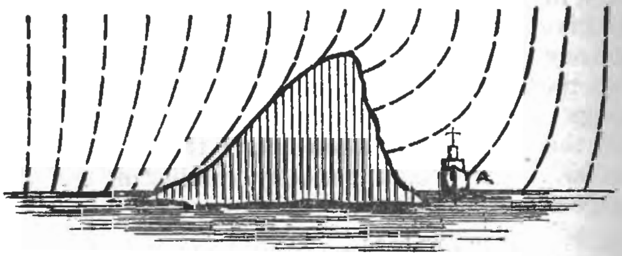


FIG. 434.

(*b*) A great deal of the available energy in the portion of the wave front with which the ship is concerned is wasted in the high ground.

This effect is very noticeable if the soil is very permeable, *i.e.*, if it contains a high percentage of iron ores.

A similar screening effect takes place if a ship is lying under a big crane, or a bridge like the Forth Bridge.

731. Atmospheric Effects.—The impossibility of seeing round corners shows that, to a first approximation at least, light waves travel in straight lines, and it might be expected that wireless waves, which are of the same nature, would travel similarly. The question then arises as to how it is possible to transmit wireless signals over the surface of the earth, which is nearly a sphere. Actually, it can be shown that even light waves do not cast absolutely sharp shadows, and can bend round corners to a slight extent by a process known as diffraction. In the case of wireless waves, which are of much lower frequency, this effect is more pronounced, and helps to explain how they can follow the curvature of the earth's surface. The tilting forward of the wave front due to surface losses was also mentioned in the last paragraph, but even when all such effects are taken into account, they are quite inadequate to account for the strength of received signals at great distances from the transmitter. There are also the observed facts that a signal which is strong at a great distance from the transmitter may not be received at shorter distances, that its strength varies according as light or darkness prevails between transmitter and receiver, and that different effects are obtained in summer and winter.

In order to explain such phenomena, it is necessary to assume that the strength of a received signal is not always that due merely, or in some cases at all, to the wave which is propagated along the earth's surface, and that part of the energy which is radiated upwards from a transmitting aerial returns to the earth's surface by a process of reflection or refraction in the upper atmosphere.

An attempt will be made in the following pages to summarise the main features of this theory, which is still very incomplete in detail. The effects observed are extremely complex, and there is considerable divergence of opinion on the conclusions to be drawn from them.

732. The Atmosphere.—Up to an average height of about 20 miles, the actual height being greatest at the Equator and least at the Poles, the composition of the atmosphere remains approximately the same as at the surface of the earth, since air currents (winds) continue up to this height. The density of the atmosphere naturally falls off as the height increases. Above this height no intermixing takes place due to air currents, and the composition of the atmosphere varies with height, the lighter gases being present in greater proportions as the height increases. There is very little definite knowledge of the composition above a height of 50 miles. It probably contains a large percentage of helium. It has also been suggested that above 70 miles the atmosphere consists mainly of frozen nitrogen particles.

In considering wireless wave propagation, the electrical properties of the atmosphere are of more direct interest than its composition. The air is nowhere a perfect insulator, but its conductivity is small near the surface of the earth. The conductivity in the lower atmosphere is mainly due to ionisation produced by the "cosmic rays" mentioned in Chapter I. Ionisation of this order is insufficient to produce any appreciable effect on the direction of wireless waves, and to provide a basis for the theory that such waves are bent round in the atmosphere and return to the earth's surface, a much greater density of ionisation must be assumed. It was first suggested by Heaviside and Kennelly that such a